A MECHANICALLY COMPENSATED SAPPHIRE OSCILLATOR OPTIMIZED FOR OPERATION AT 40 KELVIN

G. John Dick and Rabi T. Wang
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

We present design features for a second-generation thermomechanically compensated sapphire resonator. Developed a few years ago, the "77K CSO" resonator showed a quality factor $Q = 2\times10^6$ at an operating temperature of 85K, enabling a frequency stability of $\delta f/f < 1\times10^{-13}$. The new design promises a frequency stability of parts in 10^{15} and can be cooled by a small cryocooler consuming several hundred watts or less. Optimization of the resonator design for a temperature of 40K results in a mechanical tuning rate requirement (MHz/micron) reduced by a factor of 8, allowing the use of a WGE mode with reduced electromagnetic fields at the surface of the sapphire and reduced losses compared to the previously used WGH mode. The lower tuning rate also contributes to higher frequency stability by significantly reducing the sensitivity to all kinds of mechanical deformation. The optimized electromagnetic design is implemented in a self-assembling mechanical configuration that allows easy disassembly for cleaning, together with first-order cancellation for expected mechanisms of physical creep. The new design shares the short thermal time constants characteristic of previously developed 10K and 77K CSO resonators. This, together with a thermal ballast methodology, allows effective compensation of temperature fluctuations over a wide range of time scales.

Corresponding Author
G. John Dick M.S. 298-100
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
USA

Phone 818-354-6393
FAX 818-393-6773

E-Mail john.dick@jpl.nasa.gov

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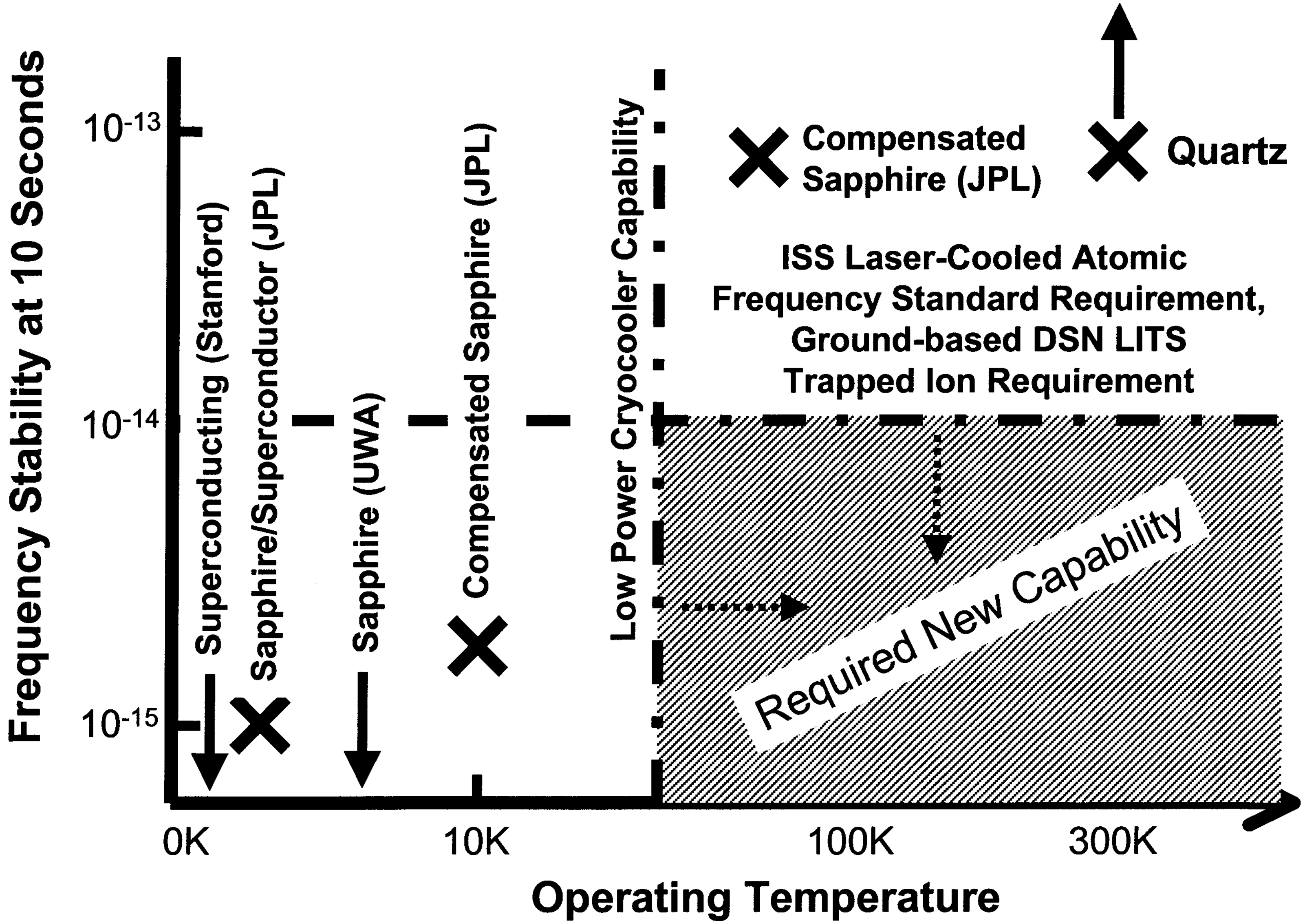
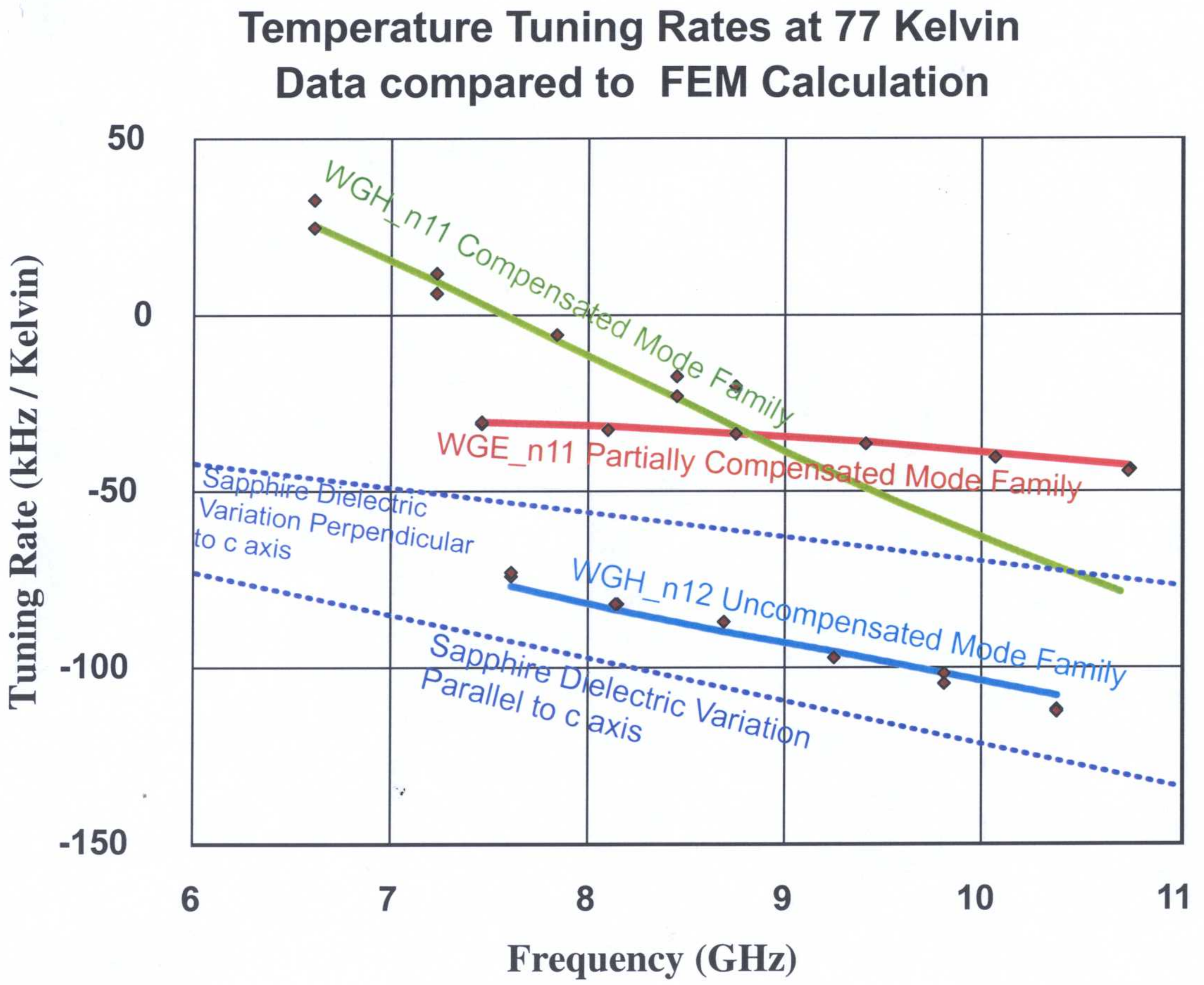
Cryocooled Oscillator

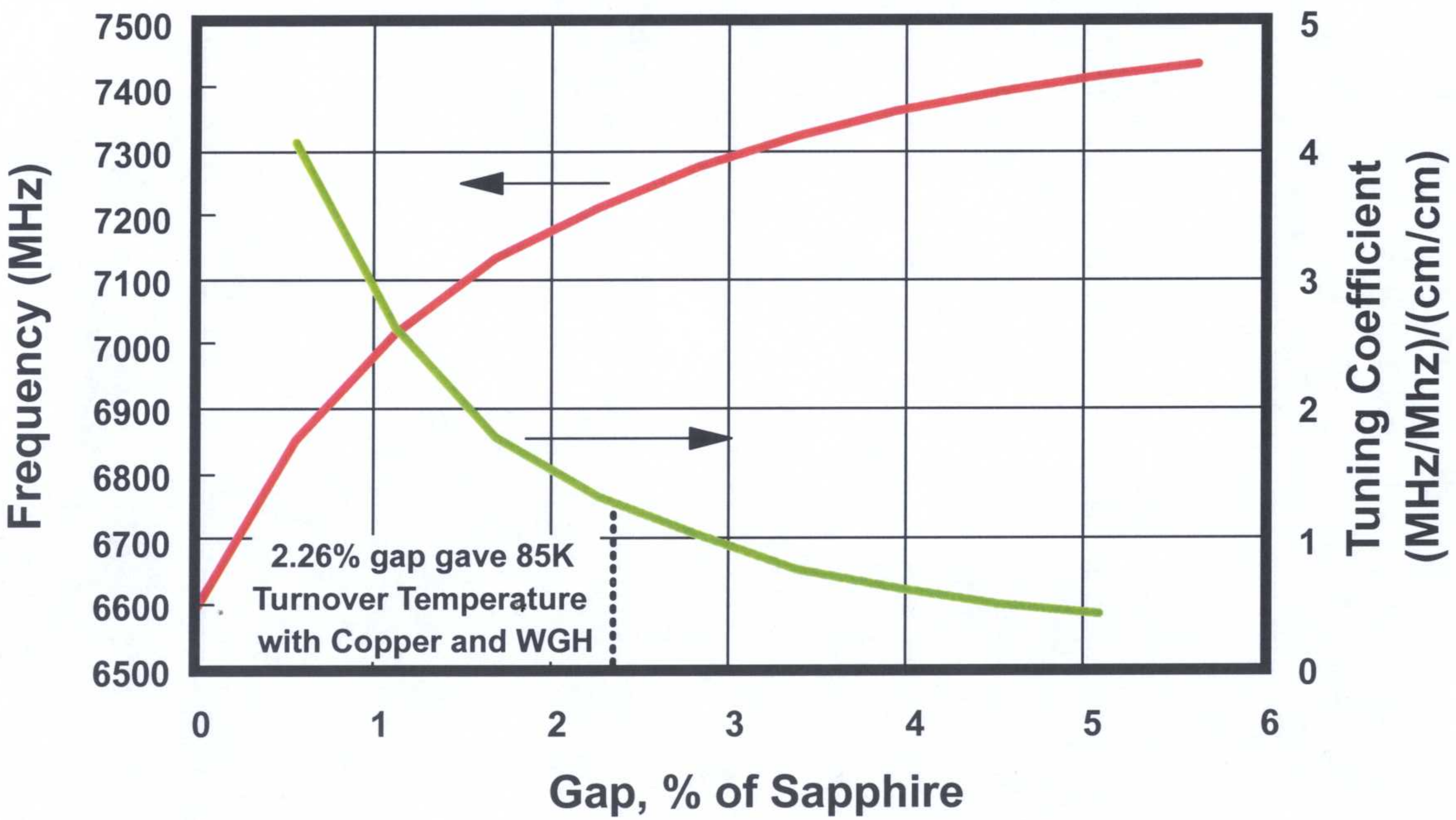
Short-Term Frequency Standard Capabilities



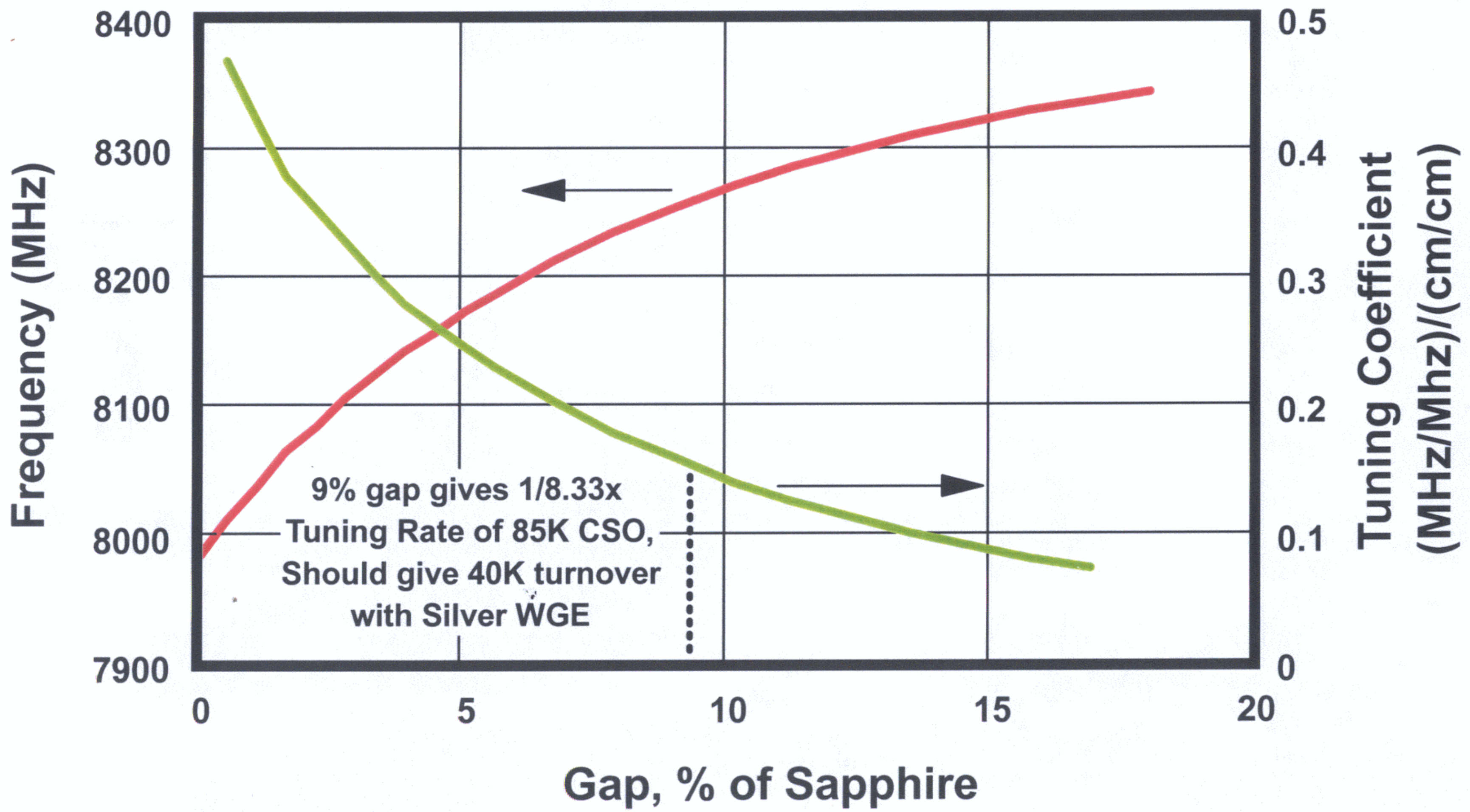


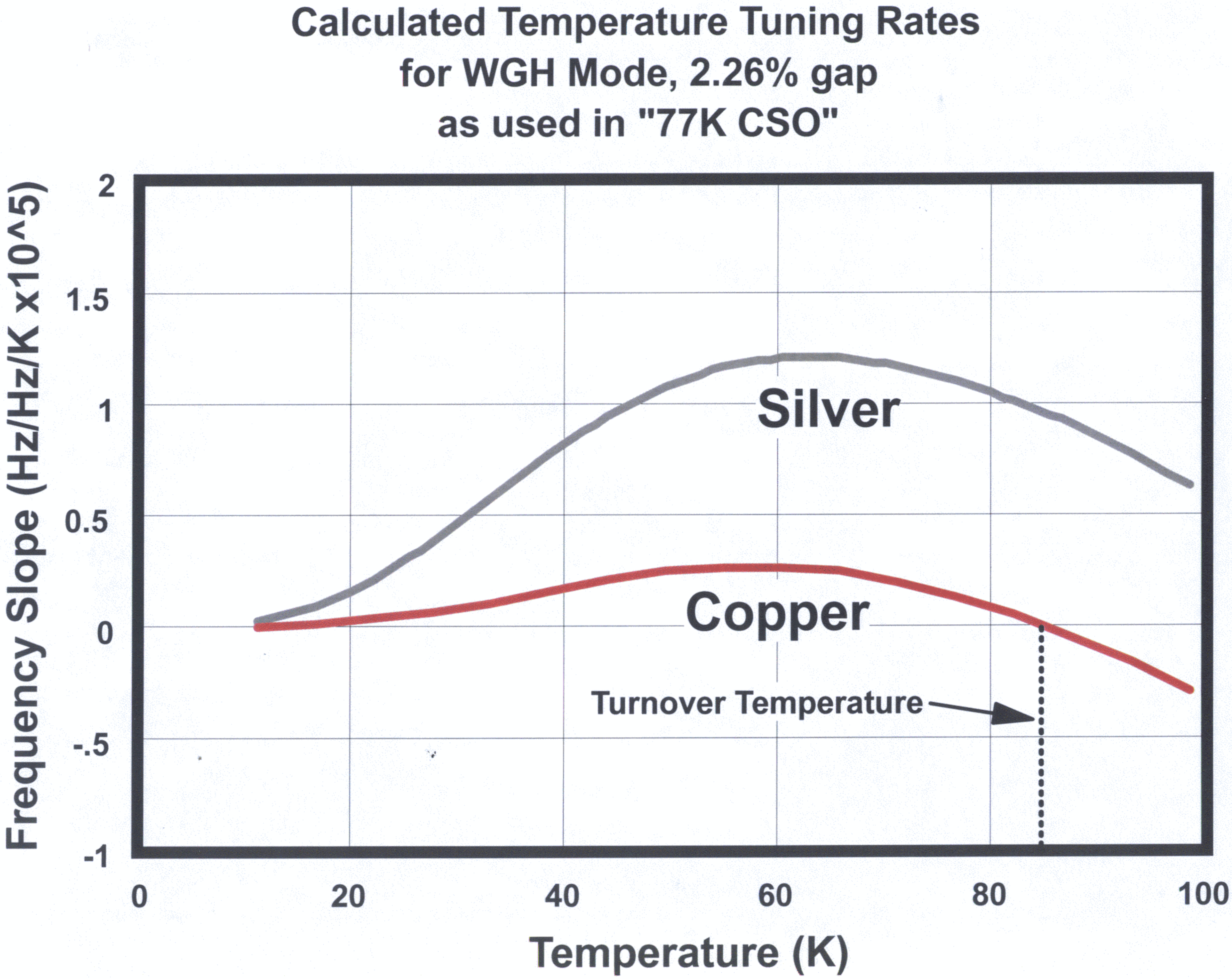
Temperature Tuning Rates at 77 Kelvin
Data compared to FEM Calculation
Tuning Rate (kHz / Kelvin)
50
0
-50
-100
-150
6
7
8
9
10
11
Frequency (GHz)
WGH_n11 Compensated Mode Family
WGE_n11 Partially Compensated Mode Family
Sapphire Dielectric Variation Perpendicular to c axis
WGH_n12 Uncompensated Mode Family
Sapphire Dielectric Variation Parallel to c axis

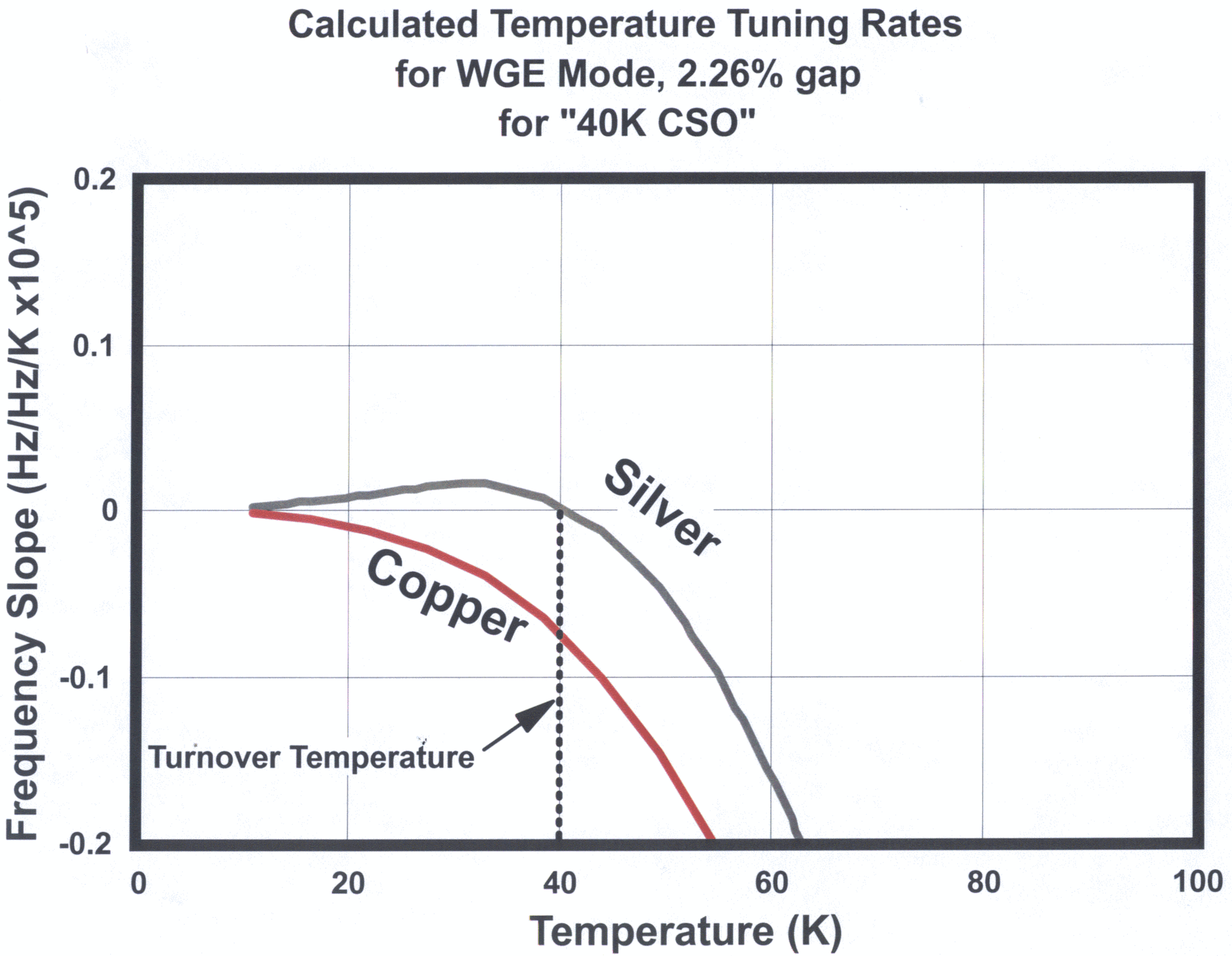
Frequency and Mechanical Tuning Coefficient for WGH "Fully Compensated" Mode

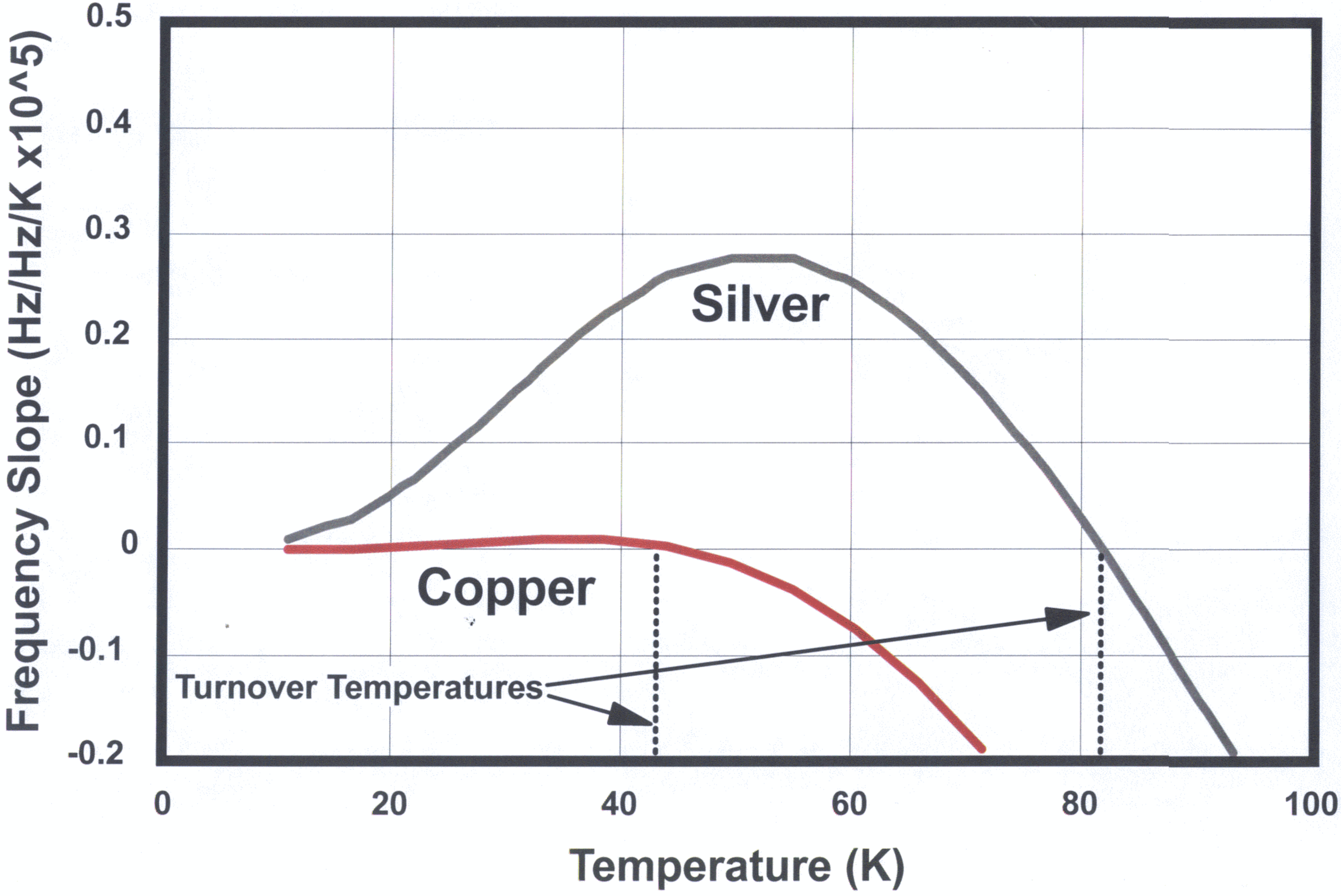


Frequency and Mechanical Tuning Coefficient for WGE "Partially Compensated" Mode

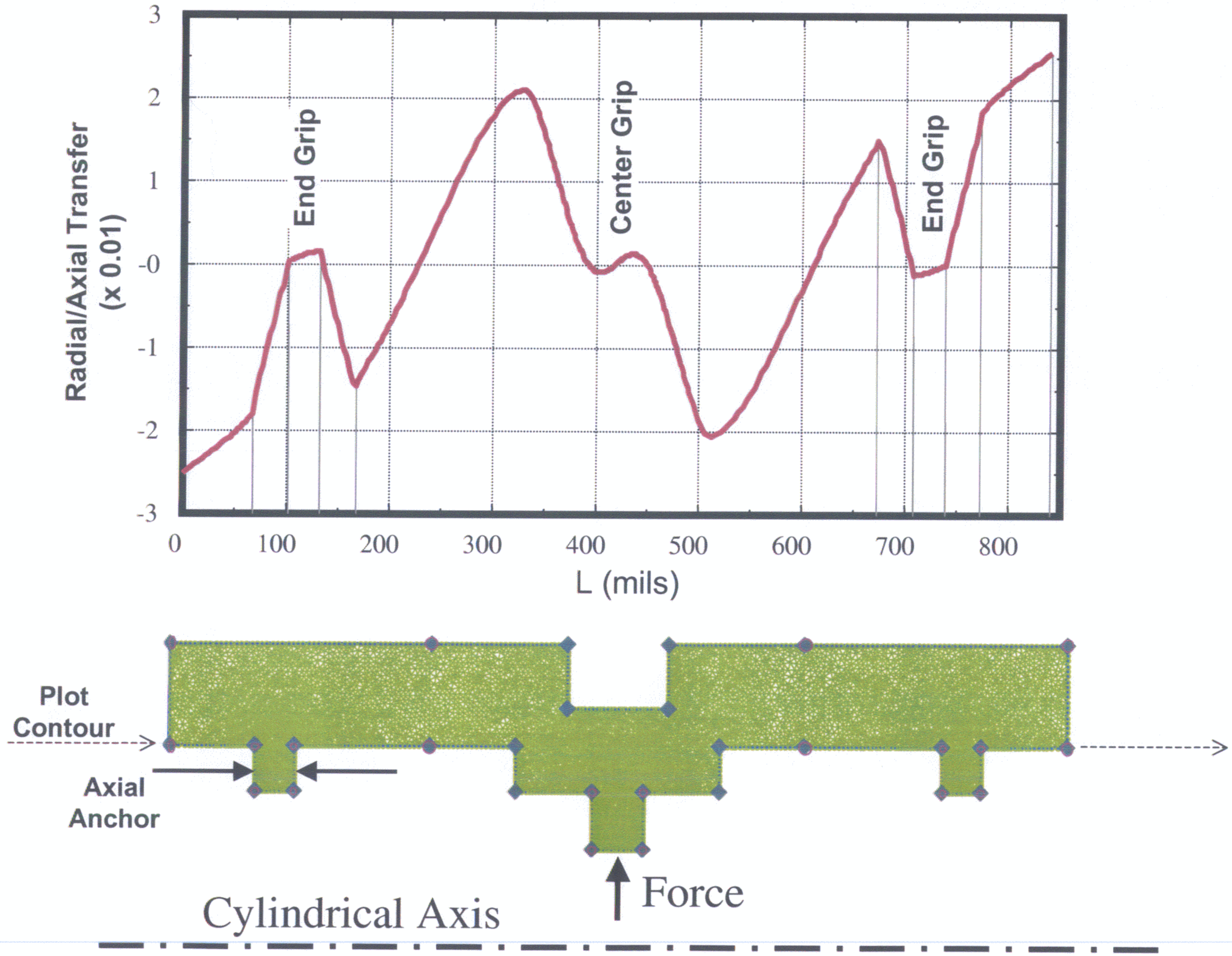



Calculated Temperature Tuning Rates
for WGH Mode, 2.26% gap
as used in "77K CSO"
Frequency Slope (Hz/Hz/K x10^5)
2
1.5
1
0.5
0
-.5
-1
0
20
40
60
80
100
Temperature (K)
Silver
Copper
Turnover Temperature


Calculated Temperature Tuning Rates
for WGE Mode, 2.26% gap
for "40K CSO"
Frequency Slope (Hz/Hz/K x10^5)
0.2
0.1
0
-0.1
-0.2
0
20
40
60
80
100
Temperature (K)
Silver
Copper
Turnover Temperature

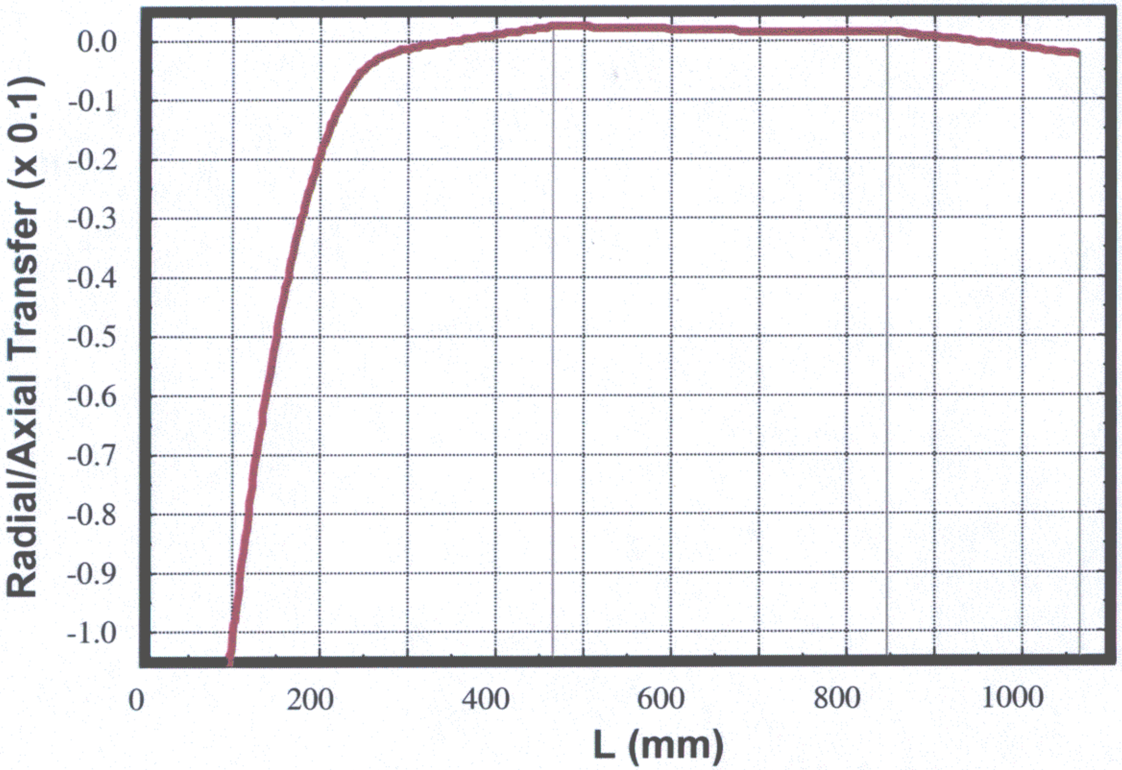


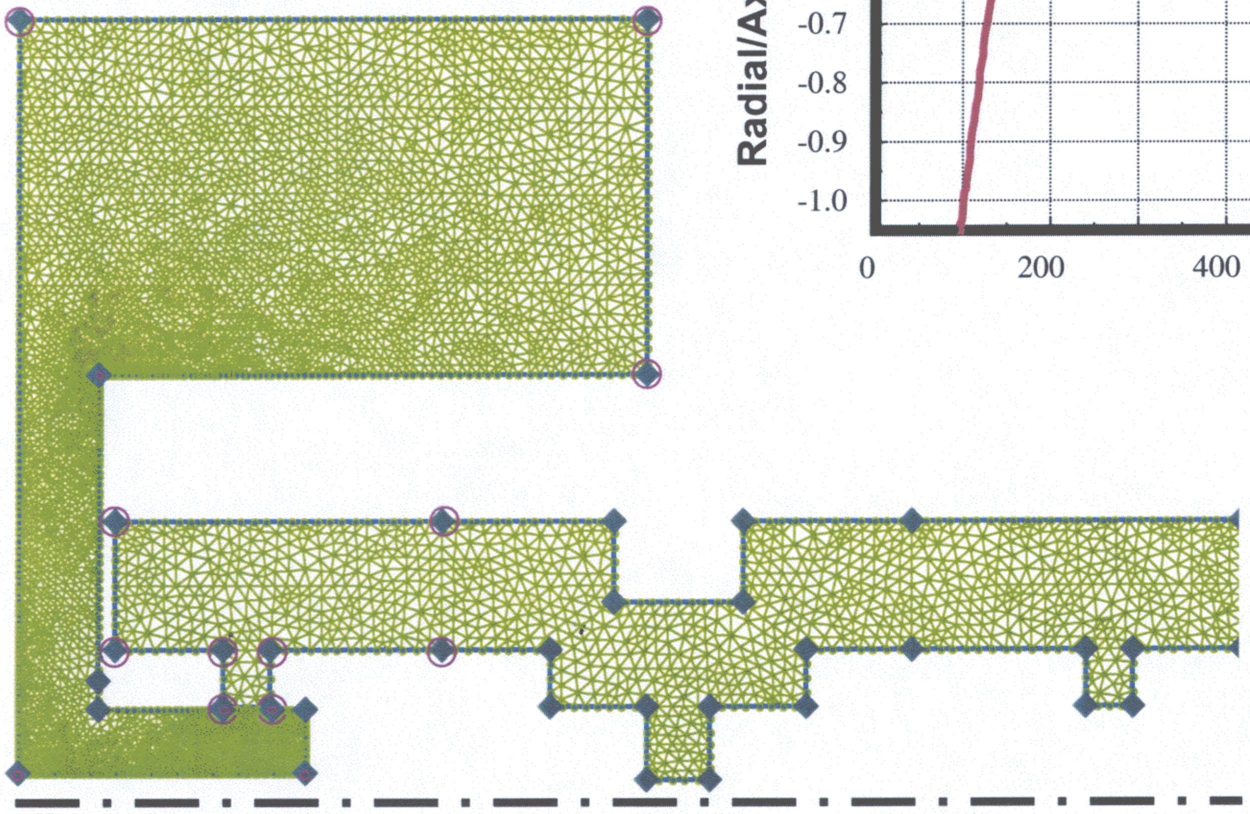
Frequency Slope (Hz/Hz/K x10^5)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Silver
Copper
Turnover Temperatures
0
20
40
60
80
100
Temperature (K)

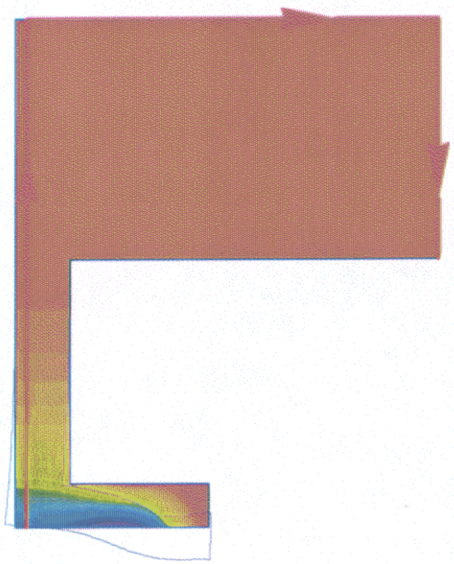


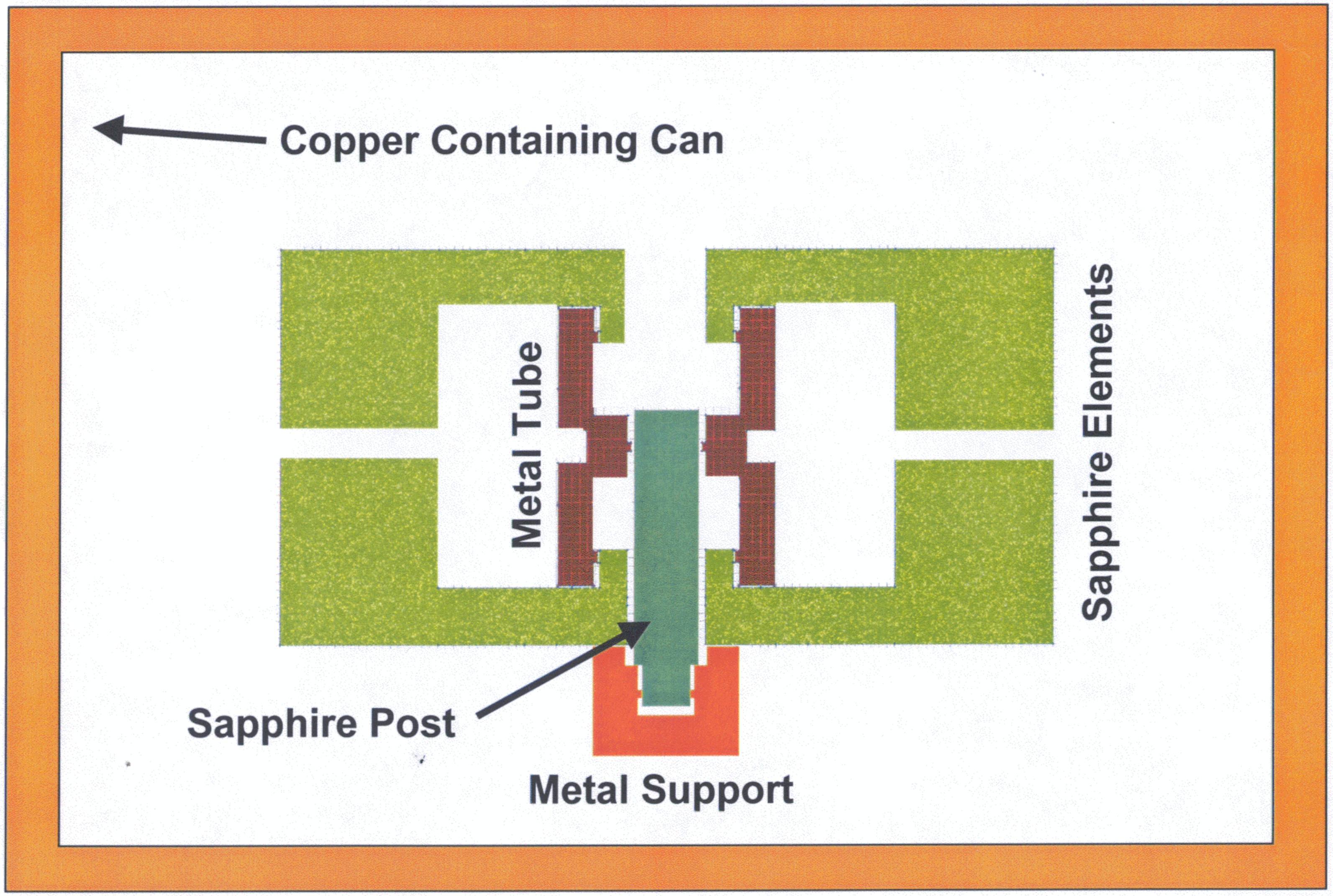
Radial/Axial Transfer (x 0.01)
3
2
1
-0
-1
-2
-3
0
100
200
300
400
500
600
700
800
L (mils)
End Grip
Center Grip
End Grip
Plot Contour
Axial Anchor
Force
Cylindrical Axis

Shortening sapphire center has same effect as thickening top plate--both give increased resonator length as copper squeezes.



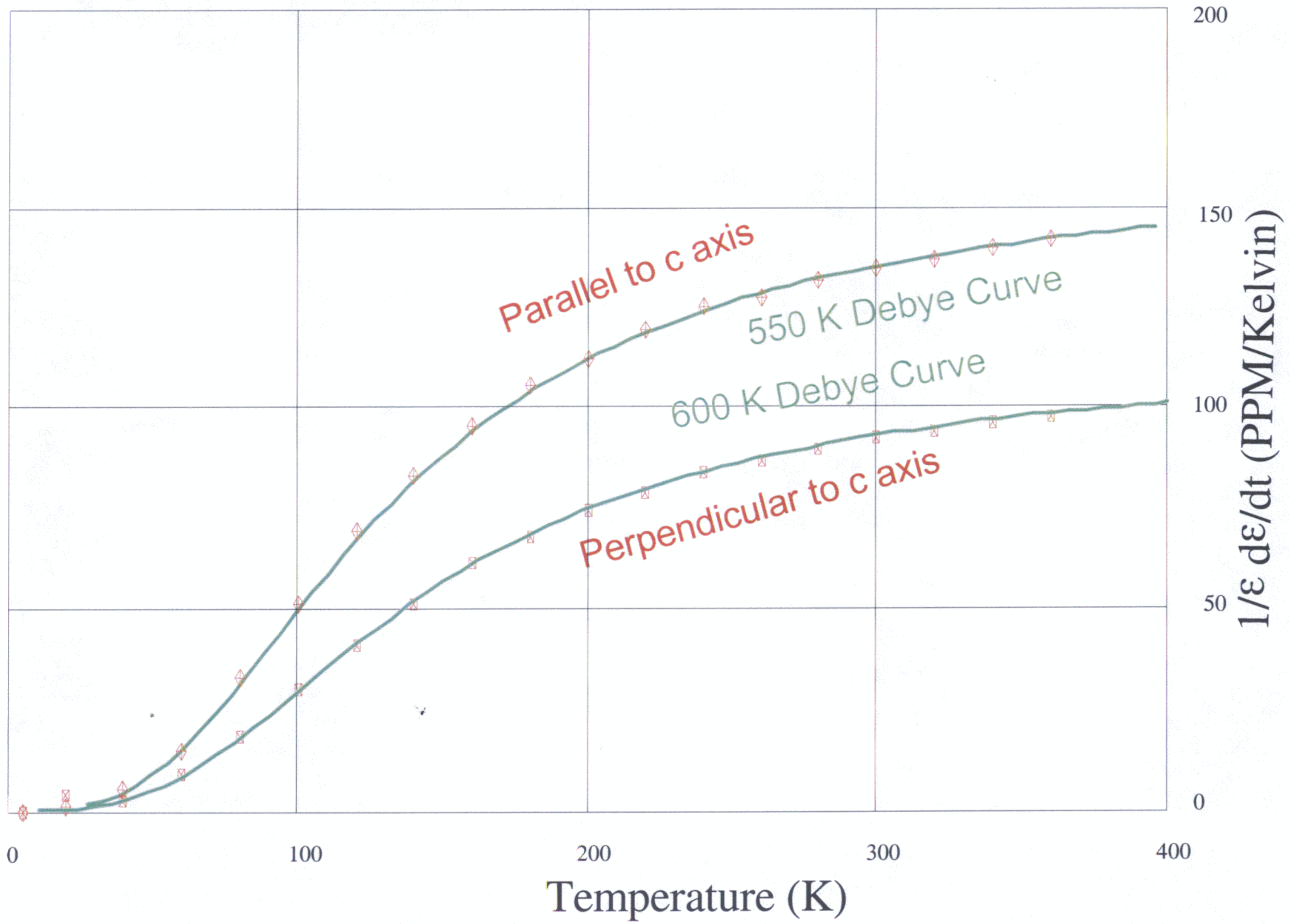


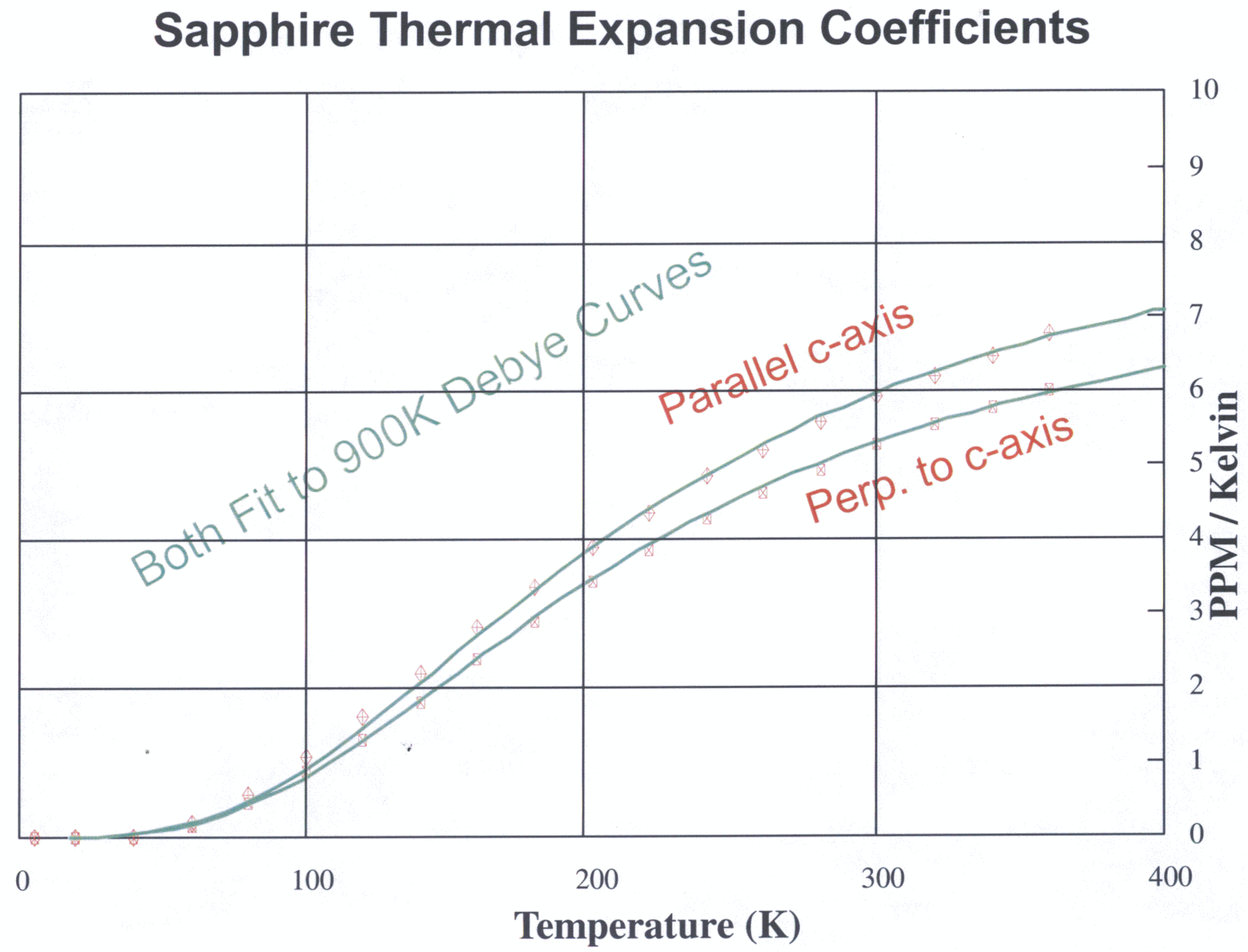


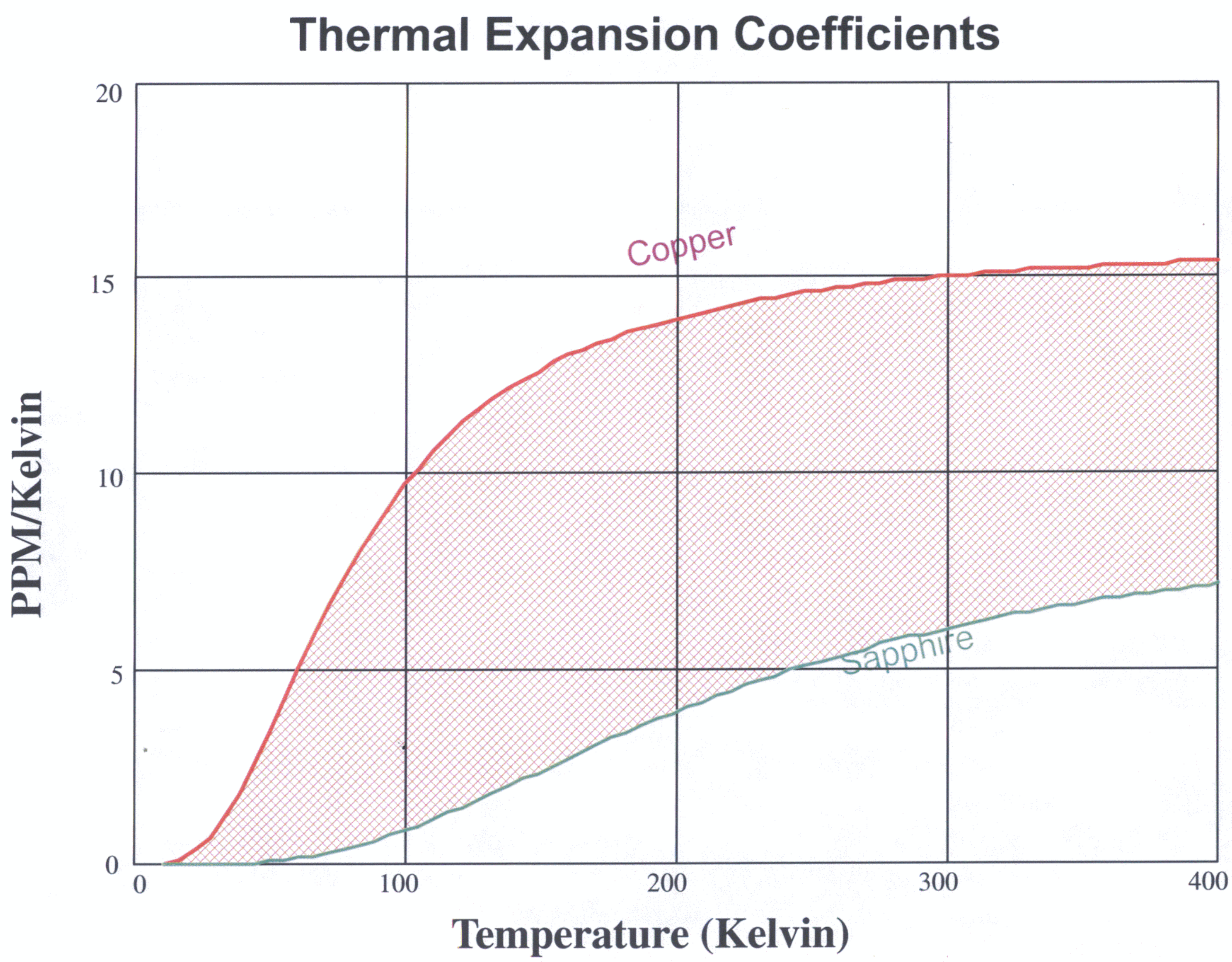


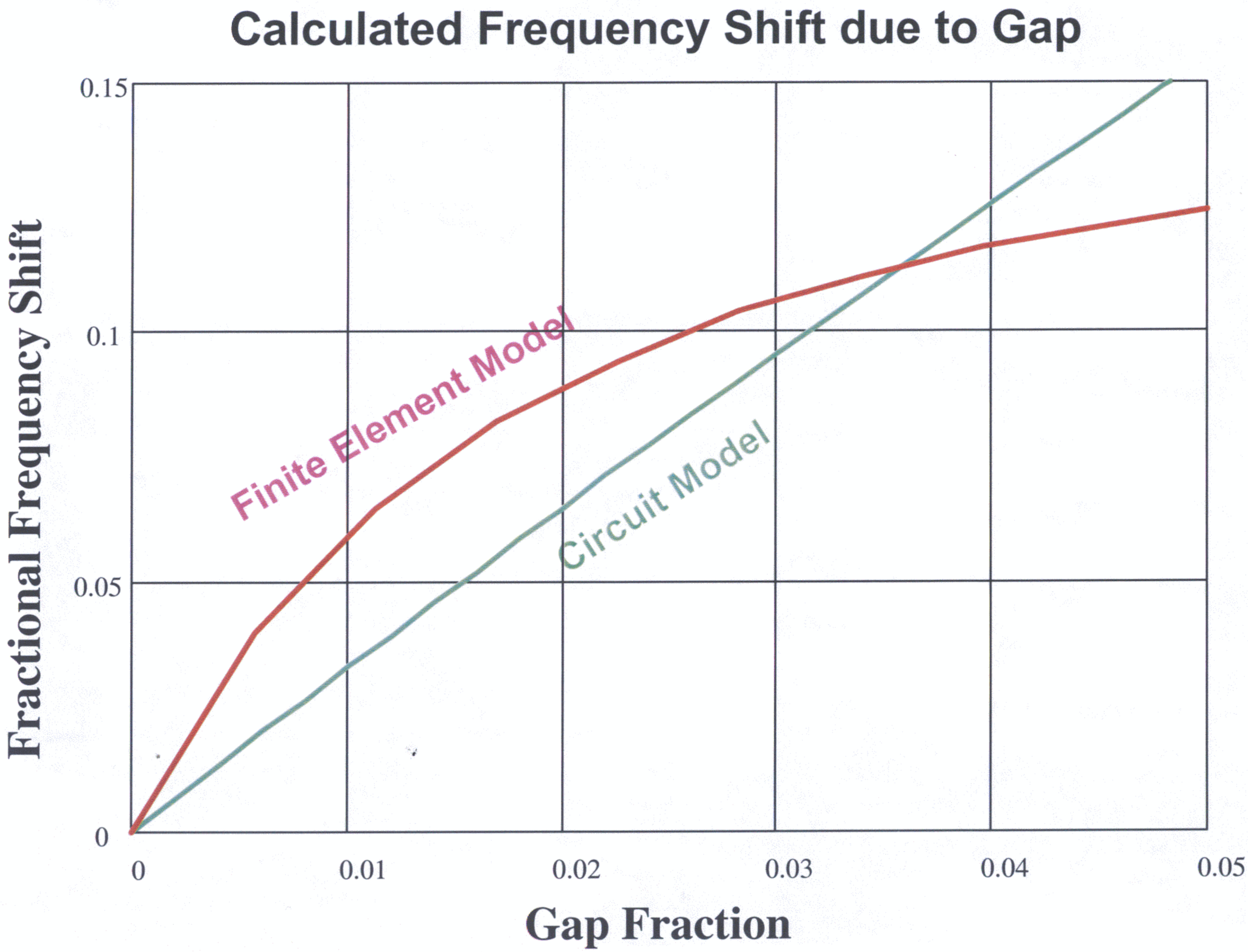
Copper Containing Can
Metal Tube
Sapphire Elements
Sapphire Post
Metal Support

Sapphire Dielectric Constant Thermal Variation




Sapphire Thermal Expansion Coefficients
Both Fit to 900K Debye Curves
Parallel c-axis
Perp. to c-axis
PPM / Kelvin
Temperature (K)
0
100
200
300
400
0
1
2
3
4
5
6
7
8
9
10


Thermal Expansion Coefficients
20
15
10
5
0
0
100
200
300
400
PPM/Kelvin
Temperature (Kelvin)
Copper
Sapphire


Calculated Frequency Shift due to Gap
Fractional Frequency Shift
0.15
0.1
0.05
0
0
0.01
0.02
0.03
0.04
0.05
Gap Fraction
Finite Element Model
Circuit Model

Electric Field Configuration for WGH_{611} Mode